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Combustion Oscillations, Extinction & Control

Final Technical Report

by

J. H. Whitelaw

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12. ABSTRACT (Maximum 200 words)

The research has involved experiments with three main flow configurations and the development of a computational method. Most of the experiments were carried out in two sudden-expansion flows, one with a plane geometry which afforded complete optical assess and the other in an axisymmetric arrangement which was closer to engineering practice but with less comprehensive optical access. A combination of optical methods was used to explore these flows which gave rise to similar flammability limits. The oscillations observed with near-stoichiometric mixtures were examined but the new main finding related to near-limit mixtures where a process of local extinction due to strain rates gave rise to low-frequency oscillations which could couple with Helmholtz and acoustic frequencies. These oscillations are related to those which lead to dynamic problems in low NOx gas turbines.

Experiments with opposed flows showed that extinction is related to the strain rates generated by impingement and that the relationship is more complex that considered here to fore. The calculation method showed that instabilities in plane sudden-expansion flows did not require consideration of time dependence and provides a vehicle for exploring different distributions of heat release rate, as found in the experiments.

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COMBUSTION OSCILLATIONS,

EXTINCTION AND CONTROL

Final Report

to

United States Army, European Research Office

Contract N68171-98-C-9020

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SUMMARY OF RESEARCH

The contract was signed on June 1998 and considerable efforts have been made to conduct the research expeditiously and to meet the stated objectives. To this end, four research students have contributed with one, Dr S De Zilwa, a Post-Doctoral Research Assistant for the past year or so. In addition, assistance has been provided by ten months of a Japanese visitor and by two visits from Professor S Sivasegaram, a previous researcher at Imperial College and now a Professor at the University of Peradeniya in Sri Lanka. There have also been important contributions to the calculation effort from Dr A Marquis.

Seven interim reports have been provided together with seven technical reports and two additional technical reports from Professor Sivasegaram. It is expected that most of these reports will be published in learned journals. References [1 to 10] show that the previous two-year contract resulted in five journal papers, two conference papers, one unpublished report and two Doctoral theses. The technical reports of the present extension include three already accepted for journal publication, one under consideration and three conference papers [11 to 17].

The objectives of the research, as described in the proposal of 1997, were to determine the extent to which discrete-frequency oscillations affect extinction of interacting flames stabilised by sudden expansions and opposed jets, including those formed by lean mixtures of gas and air, and to assess possible methods of representing the effects by a theoretical model. The proposal for the extension emphasised mixtures close to extinction, the appraisal of calculation methods and the further consideration of the link between the flows at the exit from the opposed pipes or nozzles and the distribution of strain rates in the stagnation plane, and their consequences for extinction. This extended objective was carried out in accord with the plan of Appendix A, taken from the proposal. It required the design and commissioning of two experimental facilities. An opposed-flow facility with improved control over the velocity distributions in the exit planes and a ducted round-sudden expansion to complement the existing plane sudden-expansion. In addition, a new method for the representation of unsteady flows has been developed with assessment of its applicability to oscillating flames.

Progress has been made in all of the tasks specified in the proposal as described briefly in the following sections and in the various technical reports cited.

The main contribution is to the understanding of the nature of flame stabilisation in the sudden-expansion flows that proved to be increasingly dependent upon strain rate as the equivalence ratio was reduced towards the lean limit. Since the mean strain rate was largest close to the step there was a tendency to extinguish the flame and the upstream location of the flame front moved downstream until the strain rate reduced to a magnitude sufficiently low to allow stable combustion. The flame then propagated upstream through the region of recirculation and the sequence recurred with a frequency which depended on the flow velocity. This process gave rise to oscillations with amplitude that increased with the rate of heat release and more so when there was opportunity to couple with acoustic frequencies. Increase in oscillation amplitude contributed to the unsteady strain rate which, in turn, made the flame more susceptible to strain rate and increased the equivalence ratio of lean extinction.

The oscillations close to the lean limit were frequency and amplitude modulated because the turbulent nature of the flow led to variations in the length of the recirculation region. This, in turn, introduced problems for active control since, although the bands of frequencies could be identified

in real time, it was difficult to alter the phase and to drive an actuator accordingly. The problem also occurred with near-stoichiometric mixtures where the existence of a single and readily-identifiable oscillation allowed its control but the lower-frequency oscillations associated with stabilisation rendered the control less effective. Suggestions to overcome this problem have been offered and will be developed in future research.

The effect of increases in instantaneous strain rate on extinction has been quantified in previous opposed-flame experiments but the exact relationship between the flow in the exit plane of the nozzles and the variation in strain rate in the region of flame extinction remains unknown. Experiments in isothermal flow have quantified the variations in static pressure for some geometries and flow rates and determined the consequent variations in axial and radial strain rates in the stagnation plane. It is apparent that the maximum strain rate does not coincide with the centre of the stagnation plane and that strain rate varies with radius so that extinction can be expected to begin at finite radii and to propagate to larger and smaller radii. Thus, opposed flames offer a simple way to determine a relative measure of the effect of strain rate on extinction but no absolute result can be expected.

A computer method has been developed to represent isothermal, sudden-expansion flows and involves the numerical solution of three-dimensional, unsteady forms of the conservation equations. Steady and unsteady results have been obtained for two- and three-dimensional equations with and without a simple turbulence model. The unsteady nature of the flows above a critical Reynolds number has been demonstrated and the results are in close accord with experiments. Thus, the three-dimensional, unsteady code is available to incorporate heat-release rates and distributions that are known or can be obtained from experiment and thereby allow numerical experiments of the phenomena described above.

CONDUCT OF TASKS SPECIFIED IN THE PROPOSAL

This section reviews the research in terms of the tasks of Appendix A and in number order. The tasks are identified and a summary of the findings reported in each case. More detail is available in the reports referenced here and made available with the interim reports. All tasks have been addressed but the emphasis has been on the low-frequency oscillations associated with high strain rates and local extinction since it was found that the other tasks depended on these findings. The last section considers some of the new questions that arise from the research and the means by which they may be answered.

1. OPPOSED-FLOW ARRANGEMENT

The arrangement previously used by Sardi [10] was replaced by one with nozzles carefully designed to minimise the thickness of the boundary layers in the exit plane. It is described in detail by Korusoy [18] and was fitted with loudspeakers in the cavity upstream of the contraction.

2. RESULTS FROM OPPOSED-FLOW ARRANGEMENT

Preliminary measurements of extinction showed that it occurred with increase in strain, as represented by increase in exit-plane velocity, and decrease in separation of the two flames. It was

noted that it occurred initially away from the stagnation plane at radii close to one diameter and propagated to larger and smaller radii. The radius at which extinction began, varied with separation and measurements of axial and radial strain rates showed that the former reached a maximum close to one diameter from the axis and the latter, with separations less than one diameter, some half a diameter from the axis. The distribution of total strain rate, figure 1, had these two peaks, the locations of which could also be recognised by observation of extinction.

The velocity profile across the exit planes revealed the expected boundary layer and also the wake-like nature of the flow in the vicinity of the axis for low values of separation. This had been observed in previous research but without comment. Measurements of static pressure, figure 2, showed that it also varied in the axial and radial directions and, together with velocity, satisfied Bernoulli's equation away from the boundary layer.

It is obvious from these results that the relationship between the flows in the exit planes of the two nozzles and the distribution of strain rate in the stagnation plane is not a simple one. It is likely that that maximum strain rate will always exist at a finite radius from the axis and that the value will increase with bulk flow for a given separation. Equally, the intensity of fluctuations in the exit planes and on the axis will provide a first approximation to the rms value of strain rate in the stagnation plane but dependent on exit-flow variations and separation. Thus, extinction results obtained in this and previous investigations are likely to be correct in relative terms but to provide inadequate information of absolute values.

3. MODEL GAS TURBINE

The greatest proportion of the research effort was devoted to experiments with the plane and round ducts since it became clear that oscillations existed with comparatively low frequencies at all equivalence ratios and were responsible for limitations in the application of active control. Thus, experiments were performed to provide understanding of these oscillations and alternative methods of control and encompassed stoichiometric and lean mixtures, references [11, 12 and 14].

The flammability limits measured in the plane and round ducts were similar as shown in figure 3. The branches of flame behind the two steps in the plane duct extinguished independently and both limits are indicated. At high equivalence ratios, the flame did not extinguish but moved from the sudden expansion and re-stabilised on the downstream end of the ducts. Thus the lean and rich extinction limits were defined as the lowest and highest equivalence ratios at which a luminous flame could be observed close to the expansion, and the two ducts gave rise to similar lean limits with extinction at equivalence ratios between around 0.5 and 0.6 and increasing slightly with flow rate. The equivalence ratios of the corresponding rich limits also decreased slightly with flow rate, and were slightly higher with the plane duct, around 1.6 compared with 1.4.

Both ducts gave rise to five distinct regimes of combustion which were characterised by oscillations with amplitudes that varied, in terms of rms of pressure fluctuations, from 110-160 dB (from 0.01 to 2 kPa). One of these was associated with large-amplitude combustion oscillations and another two with the instabilities close to the lean and rich extinction limits. The remaining two involved relatively stable combustion and small amplitudes, with one at low velocities and near-stoichiometric mixtures which was associated with the roll-up, growth and convection of combusting vortices at a discrete flow-dependent frequency, while the other was characterised by

vortex pairing. Further information of these regimes of nominally stable combustion has been provided by De Zilwa *et al.* [16].

Combustion of premixed methane and air in the ducted plane sudden-expansion, at equivalence ratios around stoichiometry and Reynolds numbers greater than around 48,000, gave rise to large-amplitude pressure fluctuations at the half-wave frequency of the duct with associated periodic change in the flame structure. The pressure signals and observation of the flame in a corresponding round duct indicated that the nature of the combustion oscillations was similar.

The pressure signals also revealed oscillations associated with low-frequency movement of the flame front and caused by the high strain rates and consequent local extinction close to the step. Thus, the flame detached from the step and the ensuing downstream translation of the flame resulted in smaller strain rates that allowed the flame to reattach to the step. The corresponding flame movements and modulations of the large-amplitude oscillations were stochastic with an acoustically-closed upstream boundary due to the variation of the length of the separation region as expected in a turbulent flow but, when the upstream end was open, locked on to the bulk-mode oscillation of the upstream cavity with near-periodic flame movement and signal modulations. These flame movements resulted in greater spatial distribution of the heat release rate so that the oscillatory amplitudes did not always increase with heat release at the highest Reynolds numbers.

These flame movements had adverse implications for the active control of the large-amplitude oscillations. They reduced the coherence between the imposed oscillations and the large-amplitude oscillations and thus reduced the effectiveness of control by imposing out-of-phase oscillations. Forcing oscillations at an alternate frequency has no such phase dependence and is thus less sensitive to the flame movements. However, the increased distribution of heat release, adversely affected both forms of control, due to the damping effect of prolonged combustion on the imposed oscillation and thus the effectiveness of both strategies deteriorated with flow rate.

As the equivalence ratio of the flow approached the lean or the rich flammability limits, the two branches of flame behind the plane expansion gave way to a single branch stabilised behind one or other of the steps. Figure 3a shows that the equivalence ratios at which this transition occurred were around 0.68 and 1.33 and invariant with Reynolds number. The following paragraphs describe the behaviour of the flame between equivalence ratios of around 0.68 and that of lean extinction and it should be noted that the behaviour was similar as the rich limit was approached.

At equivalence ratios slightly higher than 0.68, the flames behind the two steps moved in the same direction at the same time and this flapping became more pronounced when the equivalence ratio reached 0.68, with displacements up to around 10 mm in the 40 mm height of the duct. After oscillating in this manner for between 5 and 10 seconds, one of the two branches of flame extinguished. The pressure spectra immediately prior to the extinction of this branch exhibited peaks at the frequencies of the longitudinal acoustic wave, the bulk-mode of the upstream cavity, and that corresponding to the flapping motion which increased from around 6.25 to 12.5 Hz as the Reynolds number increased from 25,000 to 52,000. The associated rms of the pressure fluctuations also increased with flow rate but did not exceed 120 dB (0.02 kPa).

Figure 4 shows two sequences of consecutive images of the flame obtained at 60 ms intervals in the presence of this oscillation at a Reynolds number of 42,000. In the first sequence of figure 4a-d, the upper flame was very strong in figure 4a with a maximum normalised CH emission intensity of around 0.9. It then weakened until, figure 4c, the maximum normalised intensity was around

0.5, and then strengthened as shown in the final figure of the sequence. In contrast the flame behind the bottom step was very weak in figures 4a and d, and strongest in figure 4c, and this out-of-phase strengthening and weakening of the flames behind the two steps is even clearer in the second sequence of figures 4e-g. Thus, the flapping oscillation was a result of periodic strengthening and weakening of the flames behind the steps, out-of-phase with each other.

Both sequences show longitudinal motion of the position of flame stabilisation and this is considered here in terms of images with normalised CH emission intensity greater than 0.3. The first sequence shows downstream movement of the flame behind the upper step from 2.2 step heights (H) from the step in figure 4a to 2.7 H in the next two figures, and back to its position closest to the step of around 1.2 H in the final image. The flame behind the lower step moved from 2.7 H in figure 5a toward the step till it reached 1.9 H in figure 4c and again moved downstream to 4.5 H in figure 4d. The second sequence shows similar movement of the two branches of flame, with the upper branch moving from 1.2 H to 3.4 H and back to around 2.7 H, and with corresponding movement of the lower flame from 2.7 to 2.2 H and back to 3.4 H. Thus it is clear that the longitudinal oscillations of the flames behind the two steps were also out-of-phase with each other.

The flames did not stabilise closer to the step than 1.2 H, and periodically moved as much as 4.5 H downstream, probably due to local extinction at the step and at downstream locations. This is consistent with extinction measurements in the opposed flames of Sardi *et al.* [3] in that the maximum strain rate occurred with the rapid change of velocity as the flow entered the expansion and caused extinction at the step. Thus, it is likely that the weakening of the branches was due to this local extinction which travelled along the shear layer until the flame re-established further downstream where the strain rates were lower and, once re-established, it propagated upstream through the relatively quiescent recirculation region with fresh reactants. This cyclic motion of the flame led to oscillations.

The two sequences of figure 4 suggest periods of the oscillation of around 180 and 120 ms, corresponding to frequencies of 5.6 and 8.3 Hz, respectively, and associated with the movement of reattachment. The rate of decay of the velocity gradient across the shear layer and of strain rate and, hence, the distance moved by the flame varied with the length of recirculation and gave rise to a range of oscillation frequencies, consistent with the spread of the dominant frequencies of the near-limit pressure spectra. Thus, there was a range of frequencies and timescales and an average for this cycle of extinction and flashback is considered in the next two paragraphs with the locations of flame stabilisation closest to and furthest from the step obtained from figure 4 used to estimate the critical velocity gradients.

The first part of the cycle was the downstream movement of the extinction from the position closest to the step at which the flame could exist, to that where the strain rate due to the velocity gradient across the shear layer became sufficiently low to allow the flame to re-establish. Assuming linear growth of the shear layer and linear decay of the velocity with distance from the expansion, negligible velocity within the recirculation region and that extinction travels at the velocity in the shear layer, the distance and time travelled by the flame from its position closest to the step to the location of the critical velocity gradient are related to $1/U_0$ and $1/U_0^2$, respectively, where U_0 represents the inlet velocity. This suggests that the distance and time of travel decreased with flow rate, with larger change in the latter.

The second part of the cycle corresponded to flashback to the location closest to the step at which it could exist and the time for this movement depended on flame speed, which was determined from the laminar flame-speed measurements of Abdel-Gayed *et al.* [21] at 328 K and, since the recirculation zone was filled with fresh reactants at near-ambient temperature, the correction for the effects of temperature was small. The average time for the complete cycle of flame movement was calculated and decreased with flow rate from 0.175 s at a Reynolds number of 25,000 to around 0.147 s at 52,000, and with frequencies of 5.7 and 6.8 Hz. These values are similar to those obtained from the pressure measurements and the visualisation, though the change of frequency with flow rate is less, probably due to the increase of flame speed with turbulent intensity, Lewis and Von Elbe [22].

Just prior to the permanent extinction of the first branch, the out-of-phase weakening and strengthening of the branches of flame became increasingly severe as can be seen from figure 4, and appeared as alternate stabilisation on one step and then on the other. In the frames after those of figure 4g the flame stabilised on the upper step with incomplete burning over the length of the duct, though it was equally likely to stabilise on the lower step.

As the equivalence ratio was lowered further towards the lean extinction limit, which is the equivalence ratio at which the remaining branch of flame blew off the expansion, the flame oscillated laterally across the width of the duct. This can be seen from the five consecutive images of figure 5, again obtained at 60 ms intervals at a Reynolds number of 42,000. The image was brightest when the flame was at the side of the duct closest to the CCD camera and weakest when the flame was furthest away. Thus, the flame moved from the side closer to the camera in figure 5a to the opposite side of the duct in figure 5c and returned in the final image of the sequence, with a period of oscillation of 240 ms and hence, a frequency of around 4 Hz.

The experiments in the round duct showed that the flame gave rise to axial oscillations immediately prior to extinction and again at frequencies much less than those associated with the acoustic characteristics of the combustor. Typical pressure spectra immediately prior to extinction at the lean limit with the open downstream end and with acoustically open and closed upstream boundaries are shown in figure 6a and b. The dominant frequencies are readily distinguished from broad-band noise and, with the open upstream end, the bulk-mode frequency of the upstream cavity is also evident. The dominant frequency increased with flow rate from around 3.75 Hz at a Reynolds number of around 17,000 to 7.5 Hz at 49,000, figure 7a, and the trend was similar close to the rich limit though the frequencies were slightly higher, figure 7b. The increase of frequency with flow rate, and its independence from upstream boundary condition and upstream duct lengths between 10 upstream duct diameters (D) and 28 D and downstream duct lengths between 9 D and 17 D, confirmed that the oscillations were not governed by an acoustic frequency of the duct and were different from those close to stoichiometry.

These results suggest that the near-limit oscillations in the round duct occurred by a similar mechanism to that in the plane duct, with the movement of extinction down the shear layer followed by flashback from a downstream location where the strain was lower. The higher frequencies at the rich limit are consistent with this proposed model of flame movement, since the flame speeds were higher, Andrews and Bradley [23]. The use of the 60 mm downstream duct instead of the 80 mm duct resulted in higher frequencies, figure 7b, due to the shorter distance travelled by the flame with the shorter reattachment length and, hence, the more rapid decay of the velocity gradient across the shear layer. The figure also shows that experiments with propane resulted in slightly lower frequencies, consistent with lower flame speeds close to the lean limit,

Abdel-Gayed *et al.* [21 and 24], and that the introduction of swirl led to slightly higher frequencies, again due to shortening of the reattachment length, Ahmed and Nejad [25].

The rms of the pressure fluctuations increased with flow rate so that, for example, the configuration with acoustically-closed upstream and open downstream ends gave rise to amplitudes at the lean limit of 111 dB (less than 0.01 kPa) at a Reynolds number of 17,000 and 128 dB (0.05 kPa) at 49,000, and the dependence on the square-root of heat release is evident in figure 8. The amplitudes did not change with upstream duct length and decreased with downstream duct lengths less than 14 D due to incomplete combustion at near-limit conditions within shorter lengths. The amplitudes of the oscillations with the acoustically-open upstream end were slightly higher with rms of pressure fluctuations of around 132 dB (0.08 kPa) at a Reynolds number of 49,000 and probably due to amplification by the bulk-mode oscillation of the upstream cavity with frequency around 27 Hz.

Constriction of the duct exit with a nozzle resulted in much larger pressure fluctuations immediately prior to extinction and this result is considered in the following paragraphs. It has implications for practical devices where higher velocities imply frequencies of order 100 Hz and of similar magnitude to longitudinal acoustic waves. Figure 7a shows that the frequencies of the near-limit oscillations were unaffected by the introduction of the nozzle and independent of downstream duct length and, therefore, of the volume between the expansion and the nozzle. This confirms that this frequency was not caused by the bulk-mode oscillation of the cavity as evident from the presence of both frequencies in the typical pressure spectra of figure 6c. Reduction in the diameter of the exit nozzle caused the amplitude of the pressure fluctuations to increase so that the 25 mm nozzle gave rise to rms pressure fluctuations up to 150 dB (0.7 kPa) at the lean limit and 152 dB (0.9 kPa) at the rich limit. The amplitude of the near-limit oscillations again increased with flow rate at the lean limit, from around 140 dB (0.2 kPa) at a Reynolds number of 17,000 to around 150 dB (0.7 kPa) at 49,000, again indicating the dependence of amplitude on heat release.

The oscillations associated with local extinction occurred at frequencies that varied with the length of the region of recirculation and therefore provided a signal which was amplitude and frequency modulated. The amplitude increased with heat release so that it may be very large under the conditions that exist in power plant. It may also exist in the presence of bulk-mode and acoustic oscillations so that any control system is required to deal with a wide range of frequencies and amplitudes and, at least in the case of those caused by local extinction, with substantial temporal variations. An immediate implication is the need for a control system with a sensor of sufficient bandwidth, a controller that can recognise and interpret the signal in real time, and actuators that can respond to the variations. This requirement is made easier by the lower frequencies associated with extinction but it remains to demonstrate that it can be achieved.

4. CALCULATION METHOD

The ability to calculate the laminar and turbulent, two-dimensional, isothermal flows of reference [11] was demonstrated in reference [13] and a new procedure has been developed to represent the three-dimensional nature of the flows. It is based on the numerical solution of conservation equations in differential form and has been devised and tested with two- and three-dimensional isothermal flows, as described in reference [19]. It has been shown to represent the isothermal-flow measurements of reference [11] and others with precision and acceptable computing times on small work-stations.

It is intended that this new procedure will provide a basis for extension to the combusting-flow experiments but requires the incorporation of the knowledge of the physical processes which led to the low-frequency oscillations described in section 3 above.

5. CONTROL CIRCUITS

The problems associated with active control of oscillations present with combustion of near-stoichiometric mixtures are evident from section 3 above and were quantified in reference [12]. This led to the abandonment of the control procedures which have been used for several years and the development of an arrangement based on rapid digitisation of the signal from a pressure transducer, and the use of this signal to control oscillations imposed by a loudspeaker. Various methods of selecting the signals to drive the loudspeaker have been attempted and the greatest success was achieved by imposing a negative pulse immediately after the pressure maximum of the low-frequency cycle, which corresponded to flame stabilisation closest to the step, was detected. This led to reductions in the amplitude of the low-frequency oscillations of up to 50 %. This research will continue with improved software and it is expected that further reductions will be achieved.

7. OPPOSED FLAMES AND COMBUSTORS

The results of reference [18] and section 2 above show that the opposed flames provide a qualitative description of the relationship between strain rate and extinction and, to an extent to be determined, a quantitative description of the relative dependence of one on the other. Since the required quantitative link is missing, the experiments concentrated on those described in references [11, 12 and 14] and in section 3 above.

8. CONTROL

The results of experiments with control are described in sections 3 and 5 together with suggestions for the future. It is clear that analogue systems are unlikely to allow the control of the modulated signals associated with stabilisation and more so in the presence of acoustic or bulk-mode frequencies, and that a digital system is required. It is necessary that the digital system operate in real time and this is facilitated by the comparatively low frequencies. Testing is best carried out with loudspeakers as actuators but cannot be used in practice so that rapid-response fuel actuators will be required and the necessary speed of response remains to be determined.

11. COMMUNICATION

The main results of the investigation have been submitted for publication in archival journals and those of references [11, 12 and 13] have already been published or accepted for publication. One further paper has been submitted for journal publication, [14], three papers will be presented to conferences, [15, 16 and 17], one PhD thesis [20] has been completed and the two reports of references [18 and 19] will be submitted for publication at a later date.

The results have also been communicated formally and informally to the Contract Monitor, Dr R Reichenbach and then S Sampath of the US ARMY and to the Director of the NASA, Ames Research Center. They are available on computer disk on request.

REMAINING QUESTIONS AND SOLUTIONS

Much has been learned about the effect of strain rate on local extinction and the consequences in terms of amplitude- and frequency-modulated oscillation signals. It is evident that these comparatively low-frequency oscillations always exist and increase in amplitude with heat release rate and more so when acoustic or bulk-mode frequencies are also present. It may be possible to reduce the effect of these oscillations by design of stabilisation devices with smaller strain rates but this may not be possible without reducing the stabilisation effect. An alternative is to make use of active control based on imposed oscillations at different frequency or phase and the preferred approach has to be determined. It is probable that the best control system will involve digitisation of the signal from an optical or pressure transducer and real-time imposition of a signal on an actuator.

The unsteady characteristic of local extinction and the resulting cyclic behaviour can be included in the calculation method developed as part of this contract. There is no need to attempt to represent the complete physics and chemistry of the processes but, rather, to use the computer programme with the effects of different strain rates determined with empirical assumptions based on experiments.

The value of opposed flames has been weakened somewhat by the present findings but they still have a role in that they can provide relative information of the effects of parameters such as oscillations of the type associated with local extinction and this should be done. At the same time, it is possible to provide a better link between the exit plane flow conditions and the variation of strain rates in the stagnation plane and this is also well worthwhile.

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APPENDIX 1: PLAN OF WORK

1. Modification of opposed-flame facility to allow modifications to the initial velocity profile including local perturbations, and to the pulsation system to allow frequencies in a range from 2 to 100 Hz.

2. Measurements of extinction as a function of amplitude, frequency and of the velocity profiles at exit from the pipes of the opposed-flame facility with emphasis on lean mixtures.

3. Arrange ducted flames with stabilisation on rings including those which form part of the wall of the duct and those which are free standing and examine the nature of the flame with mixtures of gas and air close to the lean flammability limit. These initial experiments will make use of qualitative visualisation of flame structure and chemiluminescence of radicals; they will be partnered by schlieren observations of the equivalent non-combusting flows.

4. Formulate and assemble equations within a computer program, to include the mixinglet of the present contract.

5. Devise and construct an improved control circuit to process signals with a range of frequencies and amplitudes, assemble a diode array to act as a sensor and modify a gasoline injector for use at low frequencies and with variable load.

6. Perform preliminary calculations of extinction, evaluate by comparison with experiments and modify the program accordingly.

7. Conduct further measurements in the two experimental facilities to determine the extent to which the results from the opposed flows match those from the parallel flows over bluff bodies. Modify the experiments as required.

8. Determine the extent to which oscillations can be controlled actively over a range of amplitudes and frequencies, including those associated with extinction and possible re-light, and modify the control system to obtain the best possible results.

9. Incorporate boundary conditions from the experiments within the computer program, solve the equations and evaluate the differences between measurements and calculation. Calculate extinction and re-light phenomena as a function of amplitude, frequencies, strain rates and equivalence ratios over a comprehensive range of values.

10. Arrange the experimental facilities to represent critical flows as determined from the calculations and measure to determine the extent to which the calculation method is able to represent model flows.

11. Assemble the results of a range of experiments and calculations so as to provide guidance for the designer of lean-burn combustors and of active control systems.

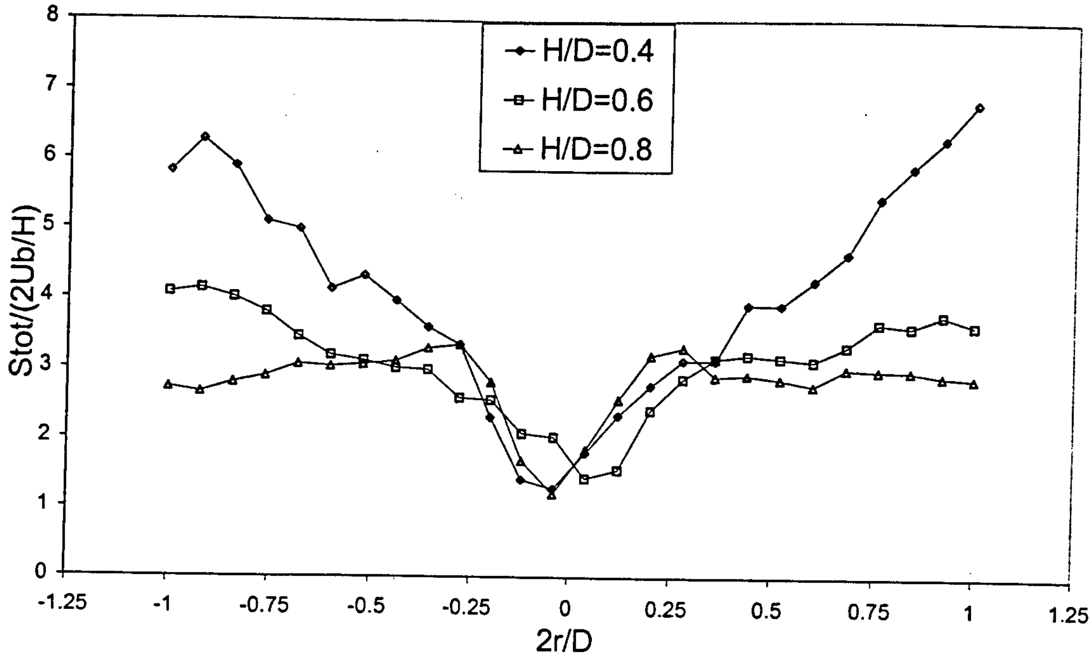


Figure 1: Radial variation of total strain at the stagnation plane in the opposed jet configuration.
Ub = 2.58 m/s, D = 25 mm.
Stot – total strain, Ub – bulk velocity, H – distance between exit planes, r – radial distance from axis of symmetry, D – diameter of burner exit.

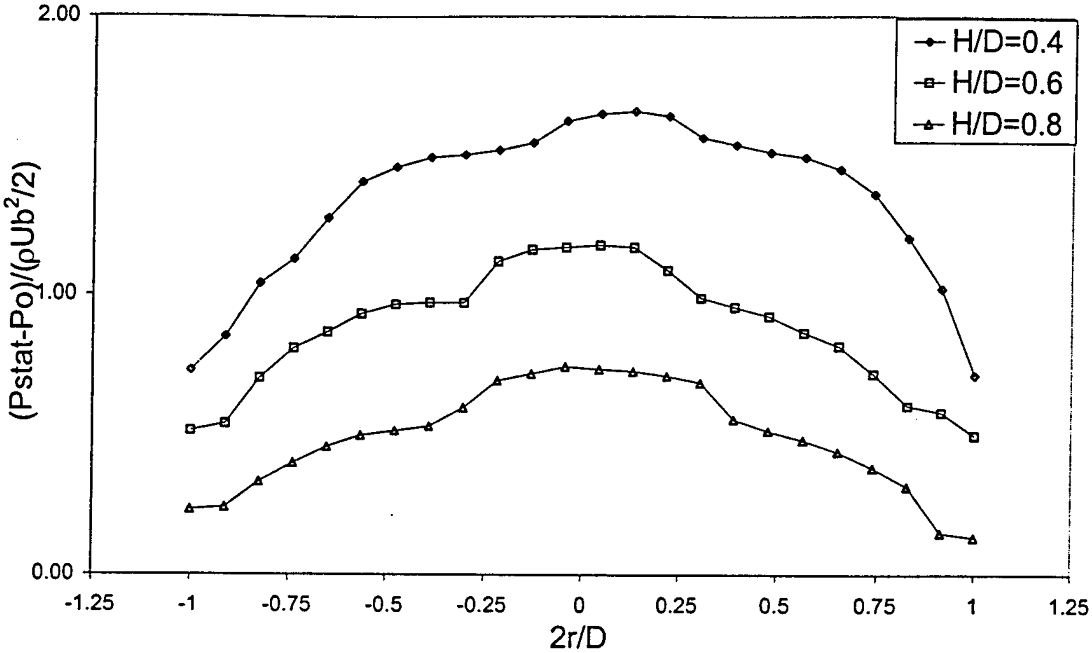


Figure 2a: Radial variation of static pressure at the exit plane in the opposed jet configuration.
Ub = 3.4 m/s, D = 25 mm.
Pstat – static pressure, Po – atmospheric pressure, ρ – density of air, Ub – bulk velocity.

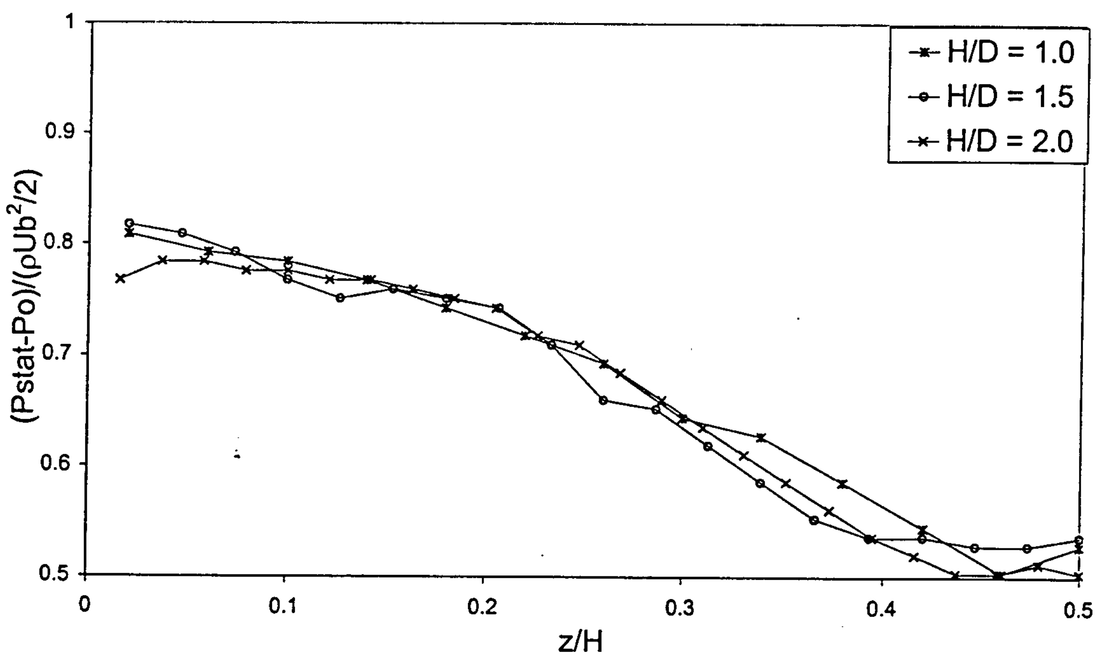
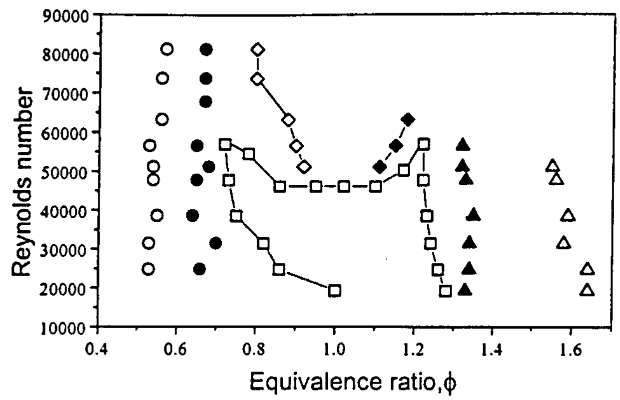


Figure 2b: Axial variation of static pressure along the axis of symmetry from the exit plane to the stagnation plane in the opposed jet configuration.
Ub = 3.29 m/s, D = 25 mm.

(a)



(b)

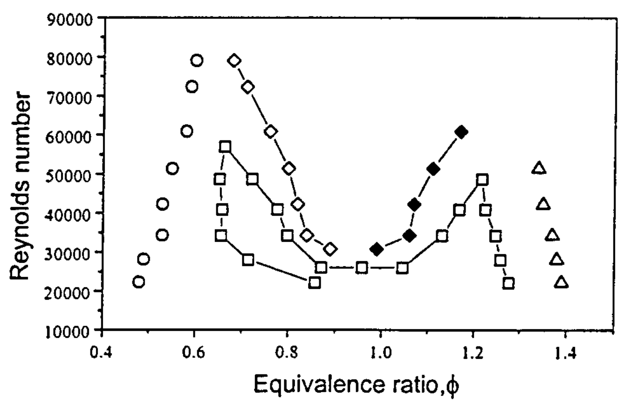


Figure 3: Limits of combustion.

(a) plane sudden-expansion configuration,
(b) round sudden-expansion configuration.

○ lean extinction limit
△ rich extinction limit
● lean extinction of first branch of flame in plane flow
▲ rich extinction of first branch of flame in plane flow
◇ lean limit of large-amplitude combustion
◆ rich limit of large-amplitude combustion
□ boundary between the two regimes of nominally stable combustion

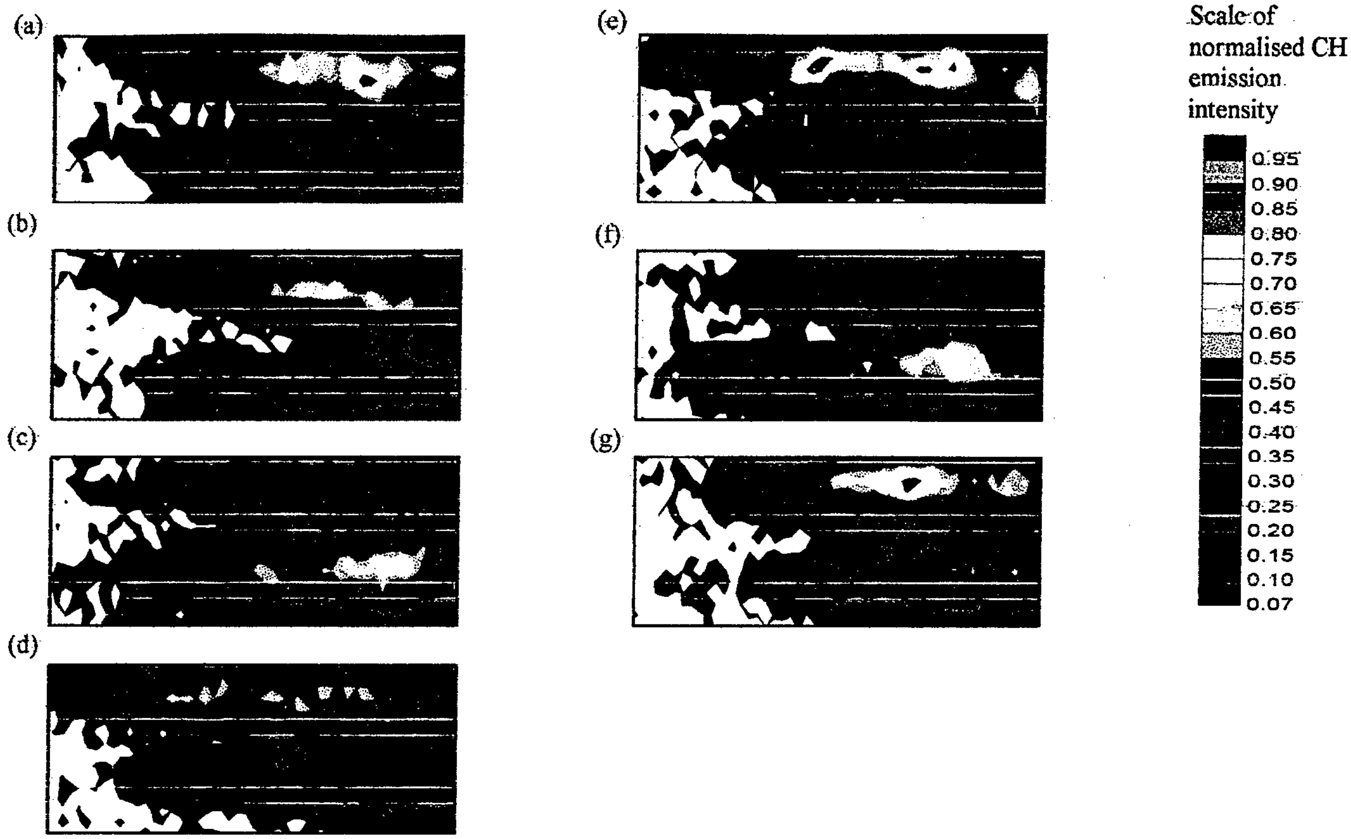


Figure 4: CH emission intensity distributions of the flame prior to the extinction of the first branch of flame in the plane sudden-expansion.
Reynolds number = 42,000, $\phi = 0.68$, exposure time = 1 ms.
Two sequences of images obtained at 60 ms intervals are shown.
One sequence, (a) – (d), was obtained between 720 and 540 ms and the other, (e) - (g), was obtained between 180 and 60 ms prior to extinction of the lower branch of flame.
CH values normalised by maximum.
Observation window height and length are 40 and 100 mm, respectively.

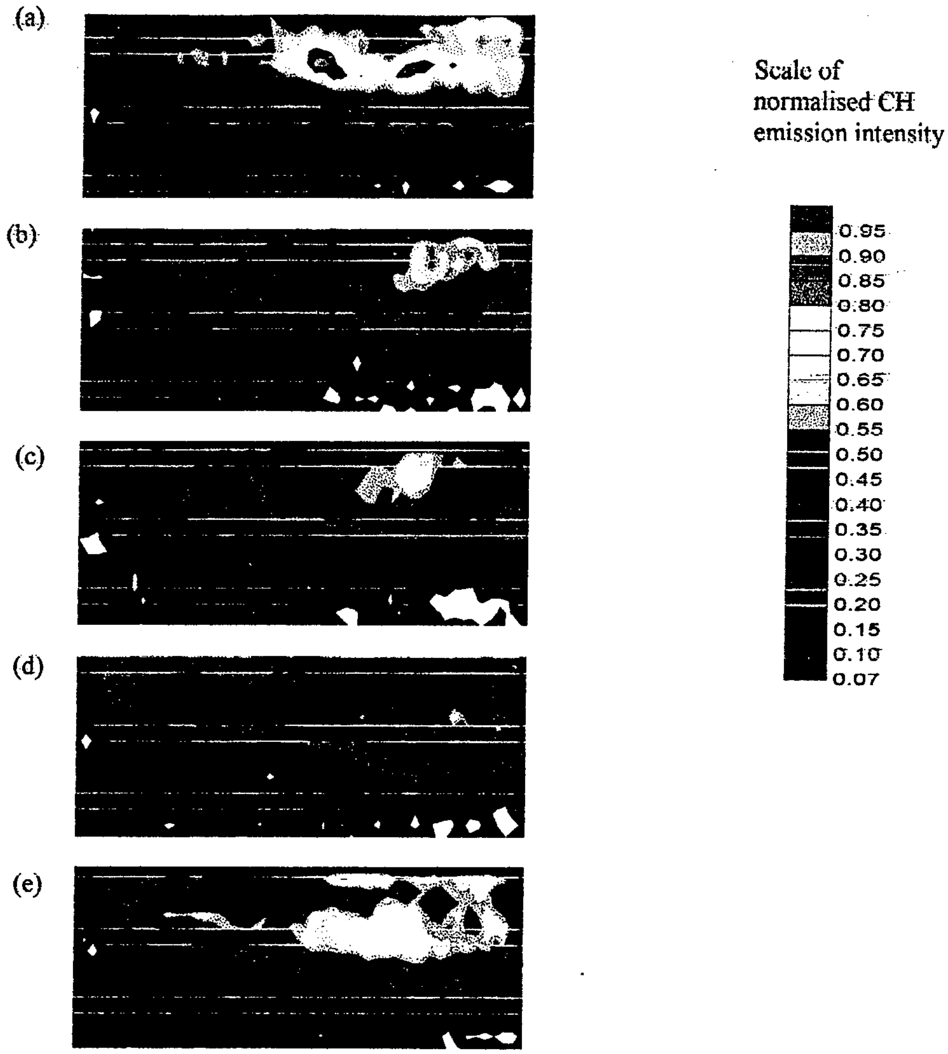


Figure 5: CH emission intensity distributions of the flame prior to the extinction of the second branch of flame in the plane sudden-expansion configuration.
Reynolds number = 42,000, $\phi = 0.54$, exposure time = 1 ms.
Five consecutive images obtained at intervals of 60 ms are shown.
CH values normalised by maximum.
Observation window height and length are 40 and 100 mm, respectively.

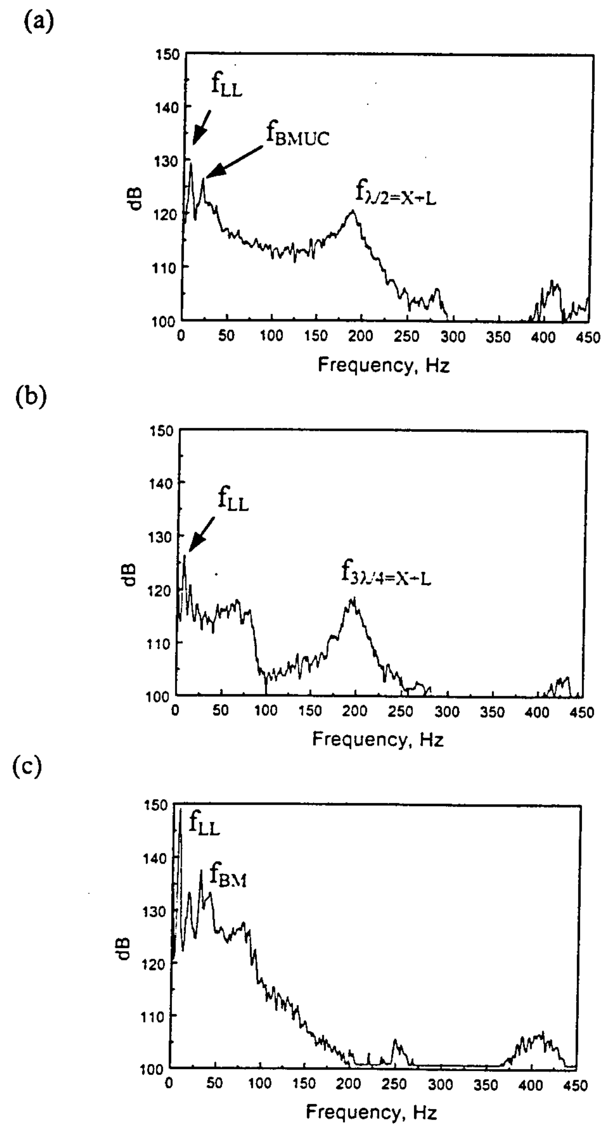


Figure 6: Pressure spectra close to the lean extinction limit in the round sudden-expansion configurations.

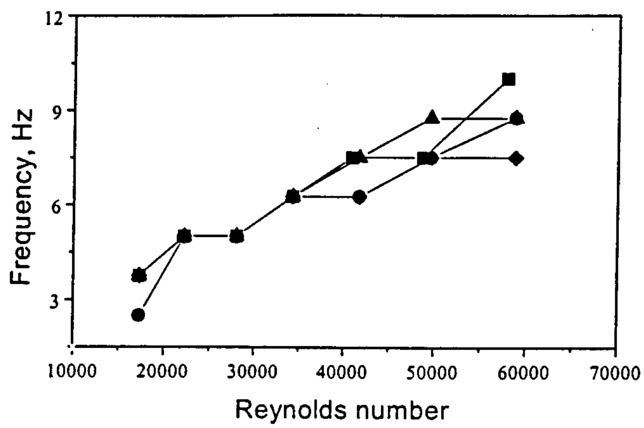
(a) acoustically open upstream and downstream ends, Reynolds number = 41,000, ϕ = 0.52,

(b) closed upstream and open downstream ends, Reynolds number = 49,000, ϕ = 0.59,

(c) closed upstream end and downstream end constricted with a 25 mm nozzle, Reynolds number = 49,000, ϕ = 0.69.

f_{LL} – frequency of near-limit oscillation, f_{BM} – bulk-mode frequency of combustor cavity, f_{BMUC} - bulk-mode frequency of upstream cavity.

(a)



(b)

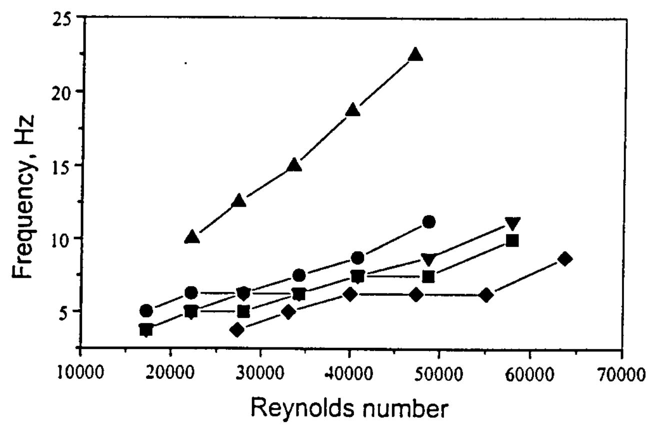


Figure 7a: Frequency of oscillations close to the lean extinction limit in the round sudden-expansion configurations.

- ■ acoustically closed upstream and open downstream ends, upstream length (X) = 19.4 D, downstream length (L) = 16.8 D,
- ▲ acoustically closed upstream end and downstream end constricted with a 40 mm nozzle, X = 19.4 D, L = 16.8 D,
- ● acoustically closed upstream end and downstream end constricted with a 25 mm nozzle, X = 19.4 D, L = 16.8 D,
- ◆ acoustically closed upstream end and downstream end constricted with a 25 mm nozzle, X = 19.4 D, L = 9 D.

Figure 7b: Frequency of oscillations close to the limit.
Base configuration is the round sudden-expansion configuration with acoustically closed upstream and open downstream ends, X = 19.4 D, L = 16.8 D,

- ■ lean limit in base configuration,
- ● rich limit in base configuration,
- ▲ lean limit with 60 mm duct replacing 80 mm downstream duct,
- ◆ lean limit in base configuration with propane replacing methane,
- ▼ lean limit in base configuration with swirl.

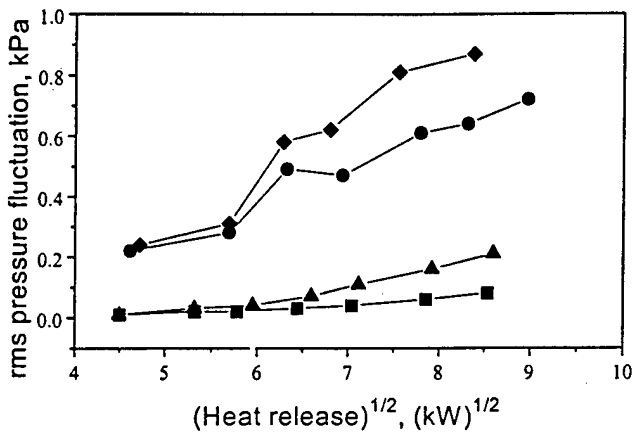


Figure 8: Amplitude of pressure fluctuations associated with oscillations close to the lean limit in the round sudden-expansion configurations.

■ acoustically closed upstream and open downstream ends, upstream length (X) = 19.4 D, downstream length (L) = 16.8 D,

▲ acoustically closed upstream end and downstream end constricted with a 40 mm nozzle, X = 19.4 D, L = 16.8 D,

● acoustically closed upstream end and downstream end constricted with a 25 mm nozzle, X = 19.4 D, L = 16.8 D,

◆ acoustically closed upstream end and downstream end constricted with a 25 mm nozzle, X = 19.4 D, L = 9 D.